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Simulated measurements of assumed ice crystal hydrometeor environments generate number-size distributions similar to those from insitu measurements even to the point of reproducing several inconsistencies often found in actual PMS data.

This paper describes the computer fabrication of ice crystals composed of single columns and combinations of columns with random spatial orientation and the simulated measuring of these particles by PMS 1-D instruments. Varying effects on the PMS distributions are demonstrated by using different assumptions of particle numbers and sizes. Efforts were concentrated on exploring the problems of deficient number counts in the first or first few classes of the PMS precipitation probe data, non-compatible number concentrations from the cloud and precipitation probes and the apparent existence of a few large particles that are not consistent with the rest of the distribution.

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This investigation indicates that the number, sizes, crystalline structure, and spatial positioning of hydrometeors may be the cause of these effects.

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SIMULATED PMS MEASUREMENTS OF ASSUMED CRYSTAL DISTRIBUTIONS

by

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1. INTRODUCTION

The early days of ice crystal measurements involved long tedious hours of counting particle imprints on coated glass slides and film or on aluminum foil that had been exposed to ice crystal populations. The introduction of the Particle Measuring Systems, Inc. (PMS) instruments by Knollenberg (1970) greatly simplified the acquisition of hydrometeor data by providing the means to electronically count and size airborne particles. These measurements produce number versus size distributions that describe particular hydrometeor situations. Thus, the problems associated with ice crystal determinations has now shifted from one of data gathering to one of data interpretation.

Typical measurements of precipitable ice hydrometeors by a PMS one-dimensional probe (1-D) show the largest number concentration at some small particle size with the numbers decreasing as the sizes of the hydrometeors increase. When the numbers are plotted versus sizes in a semi-logarithmic format, that decrease is found to be systematic and can be approximated by a straight line. Thus, number versus size distributions may be described by exponential functions. This phenomenon was also found in measurements of rain and was first reported by Marshall and Palmer (1948). The similarities in the shapes of measured number density distributions, both liquid and ice, gives rise to the possibility that all precipitable hydrometeors may naturally exist in exponential form.

There has been however, several reoccurring inconsistencies in ice crystal data from the 1-D precipitation probe that are difficult to explain. For instance, although the major portions of those type distributions may be described by exponential functions, the first or first few class sizes frequently show deficient number counts as cited by Houze, et al. (1978). One possible explanation is that evaporation may be the cause.

Another problem is non-conforming number counts in the larger-sized classes of precipitation that generally indicate concentrations larger than that predicted by the exponential trend formed by the majority of points.

Reoccurring disturbances are also present in the measurements recorded by the cloud probe. Plots of those number densities display many varied shapes and often have values in their larger-sized classes that do not conform with those from the rest of the distribution and/or with those from the precipitation measurements. Also, in many cases, there are disparities in the normalized numbers (i.e. numbers per millimeter bandwidth) in the overlapping size region of the cloud and precipitation instruments.

Figure 1 is a number density plot that shows examples of the incon-

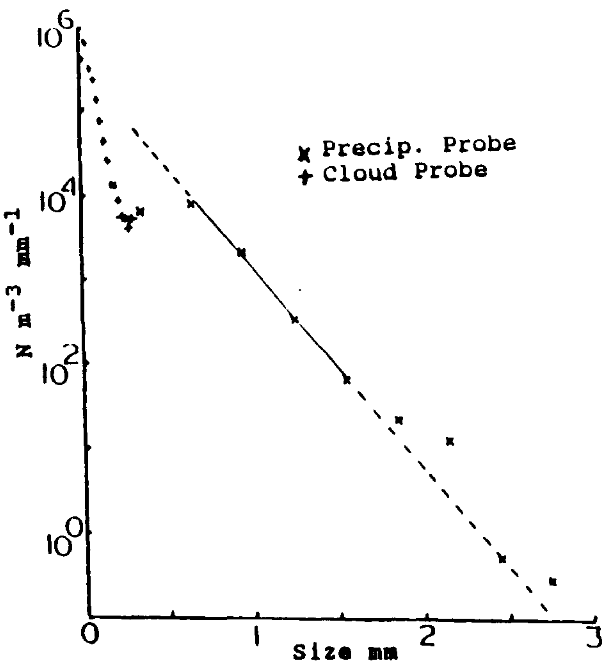

Fig. 1. PMS 1-D data taken on 15 Feb., 1979 at an altitude of 5562 meters and temperature of -29.2° C. Crystal habit was identified as being columns.

sistencies mentioned above. The data were recorded on 15 February, 1979 at an altitude of 5562 meters and temperature of -29.2° C. The predominant crystal type was identified as being columns.

A study, conducted at the Geophysics Laboratory (Berthel, 1981) explored the measurement of various shapes of ice crystal forms by a PMS instrument. The data were simulated by specifying distributions of numbers and sizes and allowing each individual crystal to have a randomly selected, spatial orientation. It was found that the measurements could be substantially different than those from the initial, actual distributions especially in cases of elongated crystalline structures.

The computer program used to fabricate single crystal measurements has since been expanded to allow the combining of individual crystals. The simulated data, in class sizes common to those of the PMS instruments, resulted in distributions similar in form to those from in-situ measurements.

2. SIMULATED MEASUREMENTS

The data used in this investigation are composed of simulated measurements of columnar crystal forms of known numbers and sizes with PMS 1-D probes.

The 1-D instrument, simply stated, consists of a series of photodiodes illuminated by a laser. A hydrometeor passing through the sampling volume occludes one or more diodes thereby producing a measurement of one unspecified dimension that is referred to, in this report, as a shadow length or L_S. The output from the analyses of the 1-D data consists of the numbers of hydrometeors contained in 15 size classes with limits predetermined by instrument construction and calibration. In this investigation, the assumed measurements of the cloud probe spans the range from 0.01 to 0.31 mm in class widths of 0.02 mm. The precipitation probe covers 0.2 to 4.7 mm in class widths of 0.3 mm.

The assumed ice crystals used in this study are solid columns with lengths (L) four times their diameters (D). A column, with L= 1 mm, passing through a 1-D instrument with the longitudinal axis aligned with the diode array in both the horizontal and vertical planes would have a L_S the same as the true length or 1 mm. If however, the column were rotated 90° in the horizontal plane, the L_S would be equal to D or 0.25 mm.

The L_S is further affected by the crystal's orientation in the vertical plane as any degree of tilt of the column's longitudinal axis from that of the diode array will result in a smaller shadow length. A 1 mm column, aligned with the diode array in the horizontal plane but with an angle of 45° in the vertical, will give a L_S of 0.707 mm. Thus, a crystal's spatial orientation in both the horizontal and vertical planes has a direct effect on the measurement obtained with a 1-D instrument.

This investigation assumes a hypothetical scenario where PMS probes are being flown through a known ice-hydrometeor environment and are measuring a specific number of columns of defined sizes. The simulation of data begins with the specification of numbers and sizes of columnar crystals. Each column is then assigned a randomly selected angle to define the position of its longitudinal axis in respect to a probe's diode array. Complete freedom is allowed in the horizontal plane and 45° in the vertical. Forty-five degrees freedom in that plane is considered reasonable for environments of average wind-shear turbulence whereas 90° would represent severe conditions and tumbling crystals. The resulting L_S is then placed in the appropriate class-size category thereby mimicking the measuring of a crystal by a 1-D instrument.

When the single columns described above are allowed to attach to one another in a random fashion, the resulting combinations display varying shapes from elongated chains to rosettes or tightly packed clusters. Figure 2 shows computer constructed combinations of 2,3,4 and 5 columns in several different configurations. Viewing these

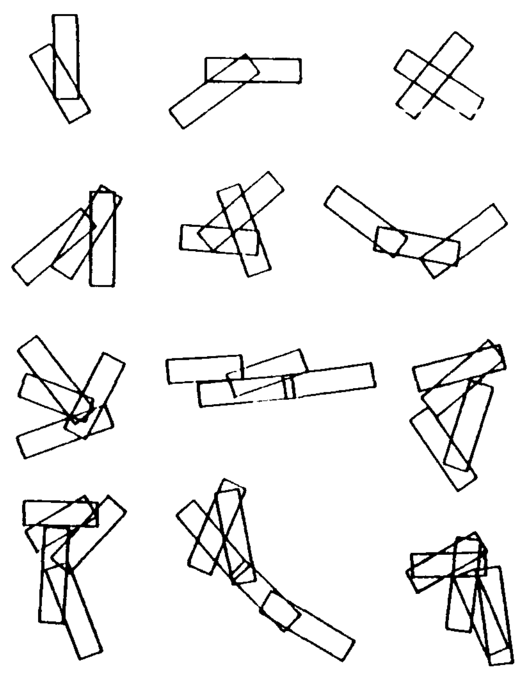

Fig. 2. Computer generated examples of combinations of 2,3,4 and 5 columns.

diagrams makes it easy to envision the myriad of measured sizes that may result from differences in crystal spatial orientation and position of attachment.

Figure 3 shows the results of the fabricated measurements of 1000 single columns with L= 1 mm in the class widths previously specified for the assumed 1-D probes and in a semi-logarithmic format common for number-density distribution plots. If each of these columns were precisely aligned with the 1-D's diode array, all of the 1000 measurements would have been contained in the third precipitation class (0.8 to 1.1 mm). Because of crystal structure and random spatial positioning, just ~45% were recorded as being in that size range with the remainder being recorded as smaller particles. Notice that some of the crystals were orientated in such a manner that the L_S values could also be recorded by a cloud probe. The numbers and sizes shown in Fig. 3, and in all the simulated measurements, represent typical examples only since random positioning will produce variations in separate simulations of identical crystals.

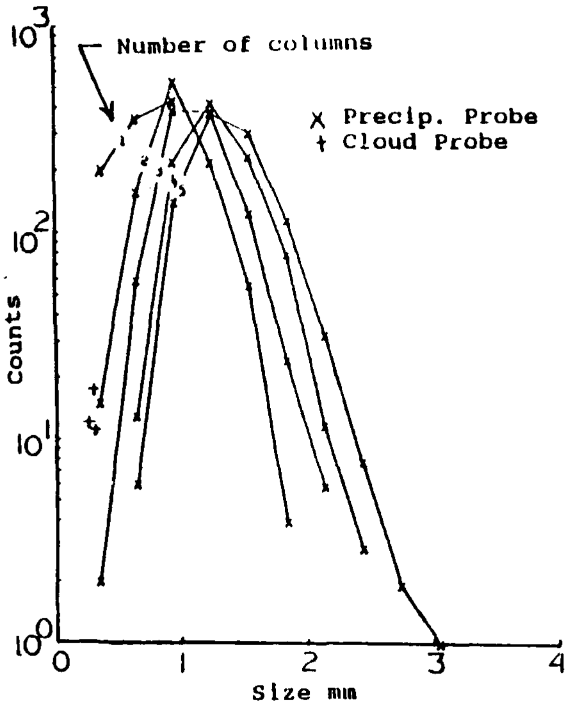

Fig. 3. Simulated measurements of 1000 single and 1000 of each combination of 2,3,4 and 5 columns.

Figure 3 also shows the simulated measurements from 1000 particles of each combination composed of 2,3,4 and 5 columns of L= 1 mm. The random selection of column positions and attachments tends to produce forms that approximate normal curves with both the peak number values and range of sizes increasing as the combinations become larger. Also, the numbers in the larger-sized classes form general exponential shapes. There are no counts attributed to the cloud probe in these four cases although the possibility does exist for any one of these combinations to attain the necessary configuration and spatial orientation to fit into one of the last three classes of that assumed instrument.

Five columns per combination are the maximum considered in this study as the mechanism of random adhesion used in this model tends to favor the stacking of crystals and produces "snowball" type structures from combinations consisting of large numbers.

Although in-situ measurements of small-sized hydrometeors are sometimes conducted in environments consisting of all single columns or nearly identical combinations, it is more common to find singles coexisting with various combinations.

A specific population of columns containing both single crystals and combinations may be defined by assigning numerical values to each hydrometeor category. This creates an assumed distribution that may be described mathematically where the concentration is a function of the number of columns making up the hydrometeors. However, it is desirable to describe the distribution in conventional terms of numbers versus sizes except that the sizes of combinations can not be specified because of uncertainties associated with the random attachment of crystals in the building of the hydrometeors. To overcome this ambiguity, the numbers of assumed hydrometeors may be defined as exponential functions of their equivalent-melted diameters (D_e) or, in other words, the diameters of the spherical-water drops resulting from the melting of the column or columns making up the hydrometeor.

If the numbers and sizes of the hydrometeors used in developing Fig. 3 are assumed to exist as a mixture, the D_e distribution forms a exponential slope (Λ) of zero. The simulated measurements of that mixture are designated by circles and squares in Fig. 4. The values in the precipitation classes display a general exponential shape for the latter portion of the distribution (solid line) with the first four showing a deficiency in numbers in respect to the extrapolated exponential (dashed) line. The deviation from exponential shape is similar to but more pronounced than that normally observed in actual PMS measurements of ice crystals. The plot also shows a small number of counts in the latter three cloud probe classes.

3. EFFECTS OF COLUMN SIZE

When the L of the individual columns are changed to 0.5 mm and the same number of single and combinations are assumed to be measured, counts are found in only five classes of precipitation with the last four being in exponential form. This distribution is coded by X's and +'s in Fig. 4. Although a difference still exists between the number in the first class and the extrapolated exponential line, the deficit is considerably less. The slope of the exponential line over the larger class sizes is also much steeper.

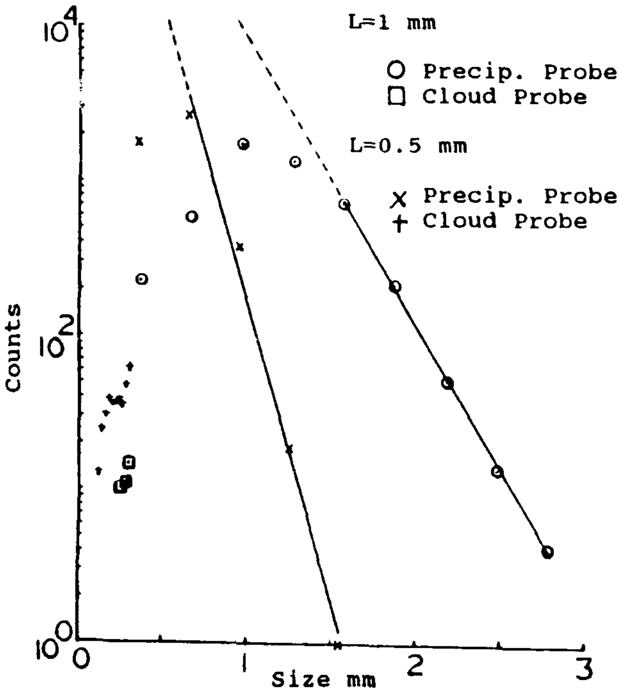

Fig. 4. Simulated measurements of assumed distributions composed of 1000 single and 1000 of each combination of 2,3,4, and 5 columns with lengths of 0.5 and 1 mm.

Another outstanding difference is that the values associated with the cloud probe are considerably greater with counts in the latter ten classes. The numbers contained in the first four of these classes (108) represent particles not included in the precipitation counts.

Simulated measurements from hydrometeors of columns with L's between 0.5 and 1 mm show the numbers in the smaller-sized precipitation classes deviating further from the exponential lines as the columns become larger. Also, the slopes of the resulting distributions become more shallow with larger particle size.

4. EFFECTS OF NUMBER CONCENTRATIONS

Variations in measurements caused by numbers of different sized particles were explored using two scenarios. First, the number of assumed single columns was large with descending amounts as the crystals combined (negative exponential slope). Second, the number of singles was small with ascending amounts as the combinations grew larger (positive exponential slope).

Figure 5 shows the simulated 1-D measurements from assumed hydrometeor distributions of single and combinations of 1 mm columns where numbers versus D_e form negative and positive slopes of 10 mm^{-1}. In the case where $\Lambda = -10\ mm^{-1}$, the last five classes attributed to the precipitation probe form a general exponential shape with the first two showing an abrupt departure from the straight-line projection. The small number of counts in the last three classes of the cloud probe are again present. The positive slope also produces a distribution showing a similar exponential slope but over a larger size range. In this case however, the first few classes display an exaggerated departure from the exponential line when compared to real data. Also, there are fewer counts in only two classes of the simulated cloud instrument.

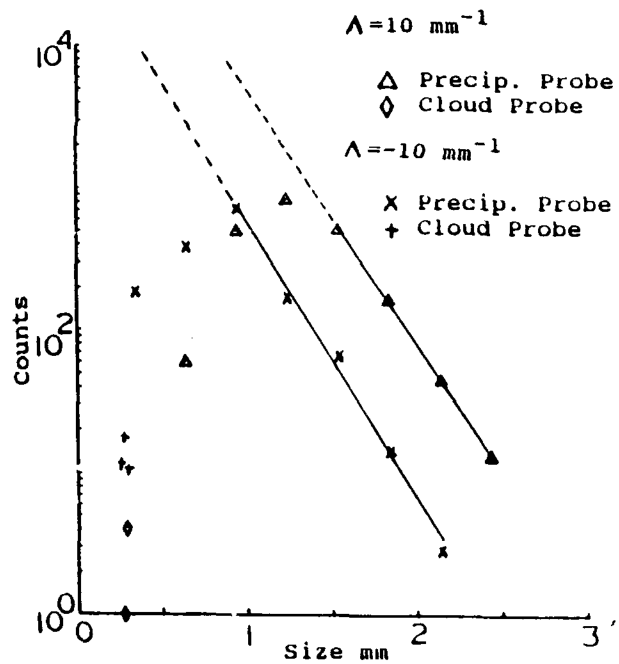

Fig. 5. Simulated measurements of assumed distributions of single and combinations of columns with lengths of 1 mm whose numbers versus equivalent-melted diameters form exponential slopes of $\pm$ 10 mm^{-1}.

It is interesting to note the similarities in the range of class sizes that form the exponential lines from the initial distribution with zero slope and from that where $\Lambda = 10\ mm^{-1}$. The plot where $\Lambda = -10\ mm^{-1}$ forms a similar

exponential but over a range of smaller sizes. It also shows more realistic numbers in the small precipitation classes.

5. EFFECTS FROM SIMULTANEOUS HYDROMETEORS MEASUREMENTS

The inconsistencies normally present in the larger-sized measurements of the 1-D precipitation probe are apparently caused by relatively few hydrometeors. Because of the nature of the semi-logarithmic number versus size distribution plot having small counts in the larger-sized classes, the addition of one of two particles may show a wide disparity from exponential shape. The random orientation of elongated ice hydrometeors may be an explanation, although this study indicates that a very low probability exists for the formation of such structures with the necessary positioning. However, if one allows the possibility of two hydrometeors to form a loose attachment and pass through the 1-D instrument simultaneously, then this phenomenon would be the anticipated result.

A simulation of this effect is shown in Fig. 6. The X's in this plot are the simulated precipitation probe measurements from columns of L=0.7 mm with single crystals and combinations consistent with the previous plots. The initial D_e distribution has a slope of $-10\ mm^{-1}$. The line shows the exponential trend formed by the last four classes.

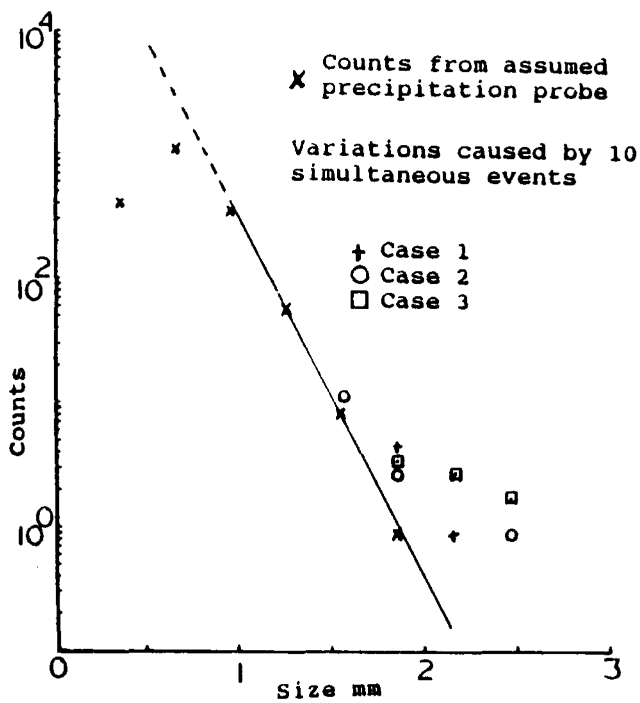

Fig. 6. Simulations demonstrating the possible effects from simultaneous measurements of hydrometeors.

Simultaneous measurements were simulated by randomly selecting 20 L_S values from this distribution, subtracting them from their classes and forming them into 10 pairs. The constituents of each pair were then assumed to be attached with new sizes equal to the sums of the individual L_S values. Classifying these combined particles thus produced an adjusted distribution with a net change in total number of just 10 hydrometeors or ~0.5%.

The results of three such adjustments displaying noticeable changes in the larger precipitation class sizes are plotted in Fig. 6 and are designated by circles, squares and crosses. Distribution shapes similar to these, where the values of the larger precipitation classes deviate from the exponential, are not uncommon in PMS 1-D measurements.

6. EFFECTS ON THE OVERLAPPING CLOUD AND PRECIPITATION PROBE REGION

The crystal type and spatial positioning of ice crystals affect the measurements from both the PMS cloud and precipitation probes. The severity of the effect is associated with hydrometeor shapes and sizes and class widths of the measuring instruments. These phenomena may help to explain some of the inconsistencies observed in the overlapping size region of the cloud and precipitation instruments.

It has been demonstrated that elongated particles may be orientated so that they are recorded in smaller class sizes than their lengths would indicate. Some hydrometeors, normally associated with the precipitation probe, may even be recorded by a cloud probe. In addition, although both probes would be exposed to the same hydrometeor environment during actual measurements, they would be sampling different particles with varying shapes and spatial positions. This adds another degree of uncertainty.

If measurements were made in an environment consisting of spherical hydrometeors with sizes that span both those of the cloud and precipitation probes, the number distributions from the two instruments, when normalized to give numbers-per-millimeter bandwidth, should form a smooth transition with number densities that accurately describe the hydrometeor population. If the spheres were changed to columnar structures, the normalized values from the two probes may conceivably be compatible but will not be true representations of the actual hydrometeor numbers and sizes. In fact, compatibility would be highly improbable because of the many uncertainties associated with the measuring of different parcels of air by the two

instruments compounded by the effects of random crystal attachment, spatial positioning and the different class widths of the probes. In such a situation, one would expect the overlapping size measurements to show the distribution from the cloud probe having higher values because of the addition of those particles that were orientated such that they were unable to be recorded by the precipitation instrument.

7. CONCLUSIONS

The investigation described in this paper used simulated measurements of assumed ice crystal environments to explore several inconsistencies that are often present in PMS 1-D recordings. The results strongly indicate that the spatial orientation of irregular or elongated particles may be the cause as they can affect both number and size measurements.

Several interesting observations surfaced during the course of this study. For instance, the simulated data show that measurements of randomly orientated, irregular particulates can produce distributions showing apparent number deficiencies in the first or first few precipitation classes. The magnitudes of those deficiencies are related to crystalline structure, particle sizes and numbers of the hydrometeors.

The major portions of the simulated precipitation measurements also form exponential shapes, as do actual data, where the slopes are dependent upon the numbers and sizes of the larger particles. The simulations of assumed ice distributions of identical sizes but with distinctly different number concentrations resulted in plots showing similar exponential slopes but over different size ranges. However, the assumption that had more large hydrometeors produced a distribution shape that showed an exaggerated departure from the exponential line in the small-sized classes when compared to actual measurements. This would seem to indicate that natural hydrometeor populations contain larger amounts of smaller particles and may, in fact, form exponential distributions.

This study also showed that measurements from the cloud probe can be adversely affected by the spatial orientation of ice crystals. These distributions may be altered by particles being recorded in smaller class sizes and may even contain counts of crystals with sizes normally associated with the first few classes of the precipitation probe. Thus, numerous variations are possible in both the cloud and precipitation measurements depending upon the particular environment at the time of sampling. On the other hand, the inconsistent scattered number counts in the larger-sized classes of the precipitation probe may be caused by the combining of hydrometeors or by the simultaneous measuring of more than one particle.

The columnar structure assumed in this investigation was chosen because it is often identified as the prevalent form in small ice-crystal environments such as that identified by Glass and Varley (1978). The random combining of these type crystals also tend to form rosettes or combinations similar to those found in nature.

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